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Future Rail Communication - Implementation Scenarios for LTE

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Problem Description

Today, Jernbaneverket uses GSM-R as their standard for cellular communication. However, this will change in the future and a proposed solution is to use LTE as the next generation standard. This work shall therefore investigate different implementation scenarios for LTE. It shall also shortly discuss the opportunities it brings to Jernbaneverket and other rail operators in general. Specifically, this means to explain different applications where LTE can be utilized and give extra benefits and features to Jernbaneverket.

Abstract

Jernbaneverket uses GSM-R in its railway network. This technology was created through cooperation in the railway sector and has established itself as the only digital railway communications standard. However, GSM-R is becoming obsolete and Jernbaneverket, together with the railway sector, need to find out when and how GSM-R should be replaced. UIC is investigating if LTE is the solution and this thesis therefore clarifies what incentives a LTE network can introduce. In addition we discuss possible implementation scenarios and how these are influenced by external and internal factors. Finally, we try to reach a conclusion on a probable upgrade year to LTE.

Results from this study show that a future LTE implementation must overcome technical, regulatory and commercial obstacles. Nevertheless, it proves itself as a promising standard that vastly outperforms the existing GSM-R solution. LTE can be used for a number of new applications and the potential for further applications are enormous. Specifically, we have identified applications that could ensure security, improve efficiency and increase profit. However, fundamental changes must be carried through and given the slow moving nature of the railway industry Jernbaneverket should start preparing now, so that it is ready to take advantage of LTE when it becomes relevant. Therefore, it should look at the internal weaknesses, external opportunities and external threats affecting a future implementation scenario for LTE. Right now, an implementation at a later point close to 2025 seems the most feasible and this gives two likely implementation scenarios. LTE will be implemented either through a parallel proprietary network, either with or without frequency partitioning, or through a national LTE network. Currently there are no clear indications that a national LTE network will be established and a proprietary implementation between 2021 and 2025 in the 700 MHz band therefore seems like the most promising solution.

Sammendrag

Jernbaneverket bruker GSM-R i jernbanenettet sitt. Denne teknologien ble skapt gjennom samarbeid i jernbanesektoren og har etablert seg som den eneste digitale kommunikasjonstandarden innen jernbane. Imidlertid begynner GSM-R å bli foreldet og Jernbaneverket, sammen med jernbanesektoren, trenger derfor å finne ut når og hvordan GSM-R skal bli erstattet. UIC undersøker om LTE er løsningen og vi forklarer derfor i denne oppgaven hva slags incentiver et fremtidig LTE-nett kan gi. I tillegg diskuteres forskjellige scenarioer som kan realiseres og hvordan disse er påvirket av interne og eksterne faktorer. Til slutt prøver vi å gi en konklusjon på når en LTE-oppgradering mest sannsynlig vil finne sted.

Resultater fra oppgaven viser at en eventuell LTE-implementasjon må løse tekniske, reglementære og kommersielle hindringer. Samtidig er det en lovende standard som er en klar forbedring fra den eksisterende GSM-R-løsningen. LTE kan bli brukt til en mengde nye anvendelser og potensialet for flere bruksområder er enormt. Vi har identifisert systemer som kan ytterligere trygge sikkerheten, forbedre effektiviteten og øke budsjettoverskuddet. For at det skal skje må det fundamentale endringer til og Jernbaneverket bør derfor starte forberedelsene allerede nå, siden jernbaneindustrien gjerne bruker lang tid på omstillinger. På den måten kan Jernbaneverket være klar til å utnytte LTE når det blir relevant. For å få til dette bør Jernbaneverket se på de interne svakhetene, de eksterne mulighetene og de eksterne truslene som påvirker en fremtidig innføringsplan for LTE. Akkurat nå virker en innføring av LTE rundt 2025 som det mest sannsynlige og det vil da være to hovedplaner. LTE vil enten bli innført via et parallelt proprietært nettverk, enten med eller uten frekvensoppdeling, eller via et nasjonalt LTE-nett. I øyeblikket er det ingen klare indikasjoner på at et nasjonalt LTE-nett vil bli etablert og derfor virker scenarioet med en innføring mellom 2021 og 2025 i 700 MHz-båndet som den mest lovende løsningen.

Acknowledgements

First of all, I would like to thank Steinar Andresen for his dedicated support and positive encouragement throughout the thesis work. His high spirit, comments and suggestions have been highly motivating and no doubt contributed to the final result of this thesis. In addition I must place my gratitudes towards Jernbaneverket. Much of the information collected has been given by the help of Martinus Grimsmo, Øystein Løkås and Ole Christian Skredsvig and they have all answered my numerous questions. Together with greatly appreciated help from Lars Moen at Mobile Norway and Peter Hausken at NSB they have helped me when I got stuck and needed clarifications. For all this I am truly grateful.

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Glossary

2G - Second Generation mobile network
3G - Third Generation mobile network
4G - Fourth Generation mobile network
AC - Authentication Centre
ATC - Automatic Train Control
BSS - Base Station Subsystem
BTS - Base Transceiver Station
BSC - Base Station Controller
CSFB - Circuit Switched Fallback
CTC - Centralized Traffic Control
DSL - Digital Subscriber Line
EIR - Equipment Identity Register
EIRENE - European Integrated Radio Enhanced Network
eMLPP - Multi-Level Precedence and Pre-emption Service
eNode-B - Evolved Node B
EPC - Evolved Packet Core
ERA - European Railway Agency
ERTMS - European Rail Traffic Management System
ETCS - European Train Control System
E-UTRAN - Evolved Universal Terrestial Radio Access Network
FA - Functional Addressing
GCR - Group Call Register
GPRS - General Packet Radio Service
GSM - Global System for Mobile Communications
GSM-R - Global System for Mobile Communications for Rail
HD - High-Definition
HLR - Home Location Register
HSS - Home Subscriber Server
ID - Identification
ISDN - Integrated Services Digital Network
IMS - IP Multimedia SubSystem
IN - Intelligent Network
IP - Internet Protocol

Jernbaneverket - The Norwegian National Rail Administration
LAS - Link Assurance Signal
LTE - Long Term Evolution
LTE-R - Long Term Evolution for Rail
M2M - Machine-to-machine
MHz - Megahertz
MME - Mobility Management Entity
MORANE - Mobile Oriented Radio Network
MPLS - Multi-protocol Label Switching
ms - milliseconds
MSC - Mobile Switching Centre
MVNO - Mobile Virtual Network Operator
NGN - Next Generation Network
NSB - Norwegian State Railways
NSS - Network and Switching Subsystem
NTNU - Norwegian University of Science and Technology
NTV - Norges Televisjon
Nødnett - The Norwegian Public Safety Radio
OMS - Operation and Maintenance Subsystem
OSS - Operation Subsystem
QoS - Quality of Service
P-GW - Packet Data Network Gateway
PLMN - Public Land Mobile Network
Post- og teletilsynet - the Norwegian Post and Telecommunications Authority
PSTN - Public Switched Telephone Network
PTT - Push-To-Talk
REC - Railway Emergency Call
RNC - Radio Network Controller
RSS - Radio Subsystem
Samferdselsdepartementet - The Royal Norwegian Ministry of Transportation and Communications
SBB - Swiss Federal Railways
S-GW - Serving Gateway
SIM - Subscriber Identity Module
SON - Self-Organizing Network

SSS - Switching SubSystem
Statens Vegvesen - The Norwegian Public Roads Administration
SVLTE - Simultaneous Voice And LTE
TETRA - Terrestrial Trunked Radio
TRX - Transceivers
UMTS - Universal Mobile Telecommunications System
UE - User Equipment
UK - United Kingdom
UIC - International Union of Railways
VBS - Voice Broadcast Service
VGCS - Voice Group Call Service
VLR - Visitor Location Register
VoLTE - Voice over LTE

1 Introduction

The Norwegian National Rail Administration (from now on called Jernbaneverket, the Norwegian name) is a state run company, responsible for the Norwegian railway's infrastructure and its operations. To carry out its duty Jernbaneverket uses GSM for Rail with GPRS as the selected telecommunication technology. This technology standard was defined by a group of manufacturers at the end of the last century to bring railways into the digital age and also to create a universal standard for railway communication. This was then adopted by the relevant standardisation bodies and has lead GSM-R to being a success story that has replaced dozens of legacy standards and is now used all over the globe. In Europe cross-border interoperability is particularly important and it has therefore received additional support from the European Commission and holds a strong position as the only standard for advanced digital railway communications.

The GSM-R network owned by Jernbaneverket is a private non-commercial network not accessible to the public. It has additional functionalities, compared to regular GSM, and is responsible for crucial operations in the daily railway work. This includes automatic train controlling and a breakdown in the system could lead to a serious accident. If the connection between a train dispatcher and a train is broken, all trains must stop. Therefore, the safety aspect has absolute priority and sets high requirements on the technology used. Jernbaneverket's GSM-R network has an extremely high quality of service requirement and it is demanded that the system functions 99,985 % of the time. Even though it copes well with its main challenges today GSM-R is becoming obsolete, especially for data usage, and it is therefore important for Jernbaneverket, together with the railway sector, to look at this technology and find out when and how it should be replaced.

Consequently, a next generation network (NGN) must fulfill these high requirements and also bring new incentives that make it reasonable to upgrade. Long Term Evolution (LTE) is the NGN that has received the highest praise and support from the International Union of Railways (UIC) and is therefore establishing itself as the main candidate. By adopting a 4G network on the LTE platform railway companies should aim to host both safety-critical communication and enhance passenger service communications on a single platform. This would then improve efficiency, enhance security and increase the attractiveness of their services. In this thesis we will therefore explain why LTE is a solution to current and especially future demands. Moreover, we will discuss possible implementation scenarios and how these are influenced by the external and internal factors that apply, thereby revealing the most promising alternatives.

The thesis is structured as follows: Chapter 2 explains the methodology and provides the necessary background to understand the architecture and functions required of GSM-R and LTE, Chapter 3 presents the different conditions and factors that affect a future implementation of LTE, Chapter 4 clarifies how a future LTE network provides incentives for an upgrade, Chapter 5 contains the different implementation scenarios, discusses the results and provides recommendations towards the most probable developments before Chapter 6 concludes the thesis.

2 Background

This chapter gives a short explanation of the methodology and a simplified introduction to the theory behind the different technologies used in mobile communication relevant to the railway infrastructure. This theory is included to give an overview of GSM-R and LTE, which are the current and proposed future technologies for Jernbaneverket.

2.1 Methodology

The idea for this thesis has been developed in coordination with supervisor Martinus Grimsmo from Jernbaneverket and the responsible professor Steinar H. Andresen from the Norwegian University of Science and Technology.

Literature has been the main source of information, but information gained through conversations and interviews with employees in Jernbaneverket, NSB (Norwegian State Railways) and Mobile Norway has also been important. In addition the magazines Tracktalk, Jernbanemagasinet and The Rail Engineer together with articles on UIC's web pages `http://www.uic.org/` and Jernbaneverket's internal wiki page `https://trv.jbv.no/wiki/Tele` have been important.

Jernbaneverket is used as a word both in single and plural form.

When Jernbaneverket as a company is addressed it is used in single form and when Jernbaneverket's employees are addressed it is used in plural form.

Some issues are not explicitly written anywhere and have only been clarified or explained by Jernbaneverket, NSB and Mobile Norway through different meetings and conversations. These are referenced as such.

Whenever near future is used in the paper this means before 2025 and whenever later point or long term is used this means around 2025 and subsequent years.

2.2 GSM-R

GSM for Rail is an international wireless communications standard that was defined by a group of manufacturers at the end of the last century. Their goal was to bring railways into the digital age and create a universal standard for railway communication. Today, GSM-R is used as a communication standard in private GSM networks built by a railway company and is designed to replace analogue radio systems by using GSM to send and receive both voice and data. It has become a major success and over 35 systems are now established in Europe alone. GSM-R is based on the second generation (2G) technology GSM and two projects called EIRENE (European Integrated Radio Enhanced Network) and MORANE (Mobile oriented Radio Network). It includes the same functionality as regular GSM and has a similar architecture, as shown in figure 2.1. However, GSM-R has extra features added that is needed in railway use. These new features include: [1]

Functional Addressing
: Functional addressing or functional numbering identifies a user by relating the number to the function a user is performing rather than a simple relation to the terminal equipment used.

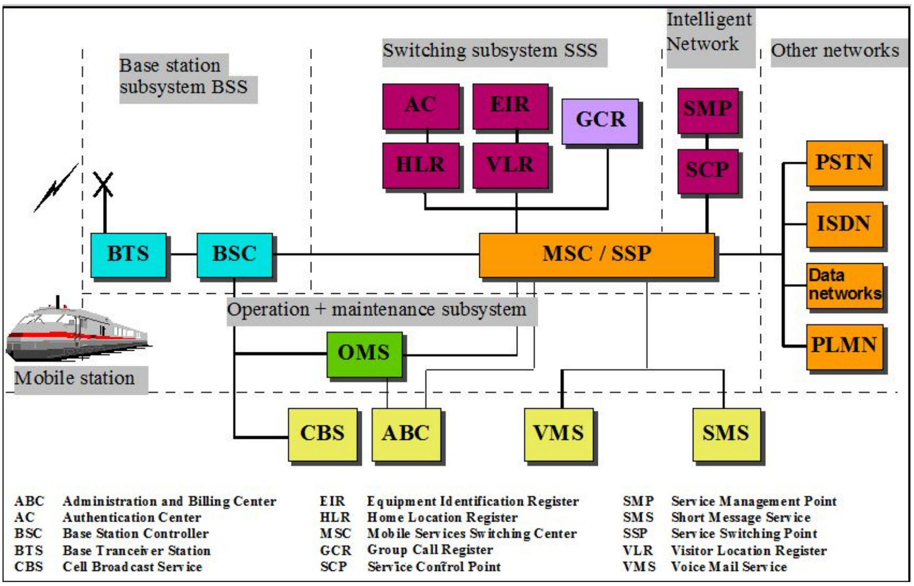

Figure 2.1: GSM-R architecture [2]

Shunting Mode

In this mode a Link Assurance Signal (LAS) is provided in order to give reassurance that the radio link is working. This mode is used when a team is manoeuvring trains in order to change their composition.

Direct Mode

This is similar to using a walkie-talkie and is back-to-back cellular radio communication that uses no infrastructure on the ground.

Multi-Level Precedence and Pre-emption Service (eMLPP)

This system introduces priority calls in the network, where 0 is highest priority and 4 is lowest.

Voice Group Call Service (VGCS)

This is a call made to all members of a group within a certain geographical area. Only one member of the group can talk simultaneously, but all users can participate in the call. This is done by using a Push-To-Talk (PTT) mechanism. By pressing or releasing it a listener can take the word and a talker can become a listener.

Voice Broadcast Service (VBS)
: This is similar to the VGCS and is defined within a certain geographical area as well, but here only the initiator of the call can speak.

Railway Emergency Call (REC)
: A REC is a voice group call service with a high priority (level 0), used to inform drivers, controllers and other personnel of a danger requiring all trains in a certain area to stop.

European Rail Traffic Management System (ERTMS)
: ERTMS is an automatic train control (ATC) system that will become common for European countries. Here GSM-R cooperates with the European Train Control System (ETCS), which is a signalling, control and train protection system. It has train-borne, trackside and lineside equipment that supervises and controls, in real-time, the train operation according to the traffic conditions.

These features put additional requirements on the architecture. The VBS and VGCS are group calls that require a database for storing group areas and group ID's. This database is integrated in the MSC. The functional addressing requires a modified Home Location Register (HLR). An Acknowledgement Center and a Monitoring Center are connected to the MSC and add functionality to the group call. These two centers cooperate and the acknowledgement center logs what happens and when it happens while the monitoring center records all conversations made, which are overwritten after a certain time. The mobile equipment also needs to support the GSM-R features. [2]

Especially the railway signalling requirements and operational voice communication are critical and essential for the railway. If these functions stop working it could lead to a serious accident and a railway network therefore have to have high focus on reliability and redundancy.

When GSM and GSM-R were established there were little focus on data transmission and they are therefore very limited in this aspect. As the world evolves data transmission will become increasingly important and these technologies will therefore become obsolete. As the next section will show, LTE is a natural solution to this for the railway industry. However, the QoS requirements also apply for a future generation of a similar railway network and an implementation of LTE must therefore fulfill the same requirements as GSM-R.

2.3 LTE

Long Term Evolution (LTE) is a fourth generation network (4G) and is characterized by being all IP (Internet Protocol). In other words the wireless industry takes the same path as DSL, fibre and broadband IP over TV and focuses on packet switching instead of circuit switching. LTE offers strong mutual authentication and optional end-to-end confidentiality protection. In addition it is a commercial off the shelf technology that does not require any modifications before it is installed. It has a number of beneficial qualities such as low latency, reduced power consumption and operating costs and a flexible architecture. When LTE first came it was introduced for a number of reasons: [3]

- Tackled user's demand for higher data rates and quality of service
- Brought an optimised system for packet switching
- Handled demand for cost reduction
- Reduced the complexity
- Avoided unnecessary fragmentation of different technologies

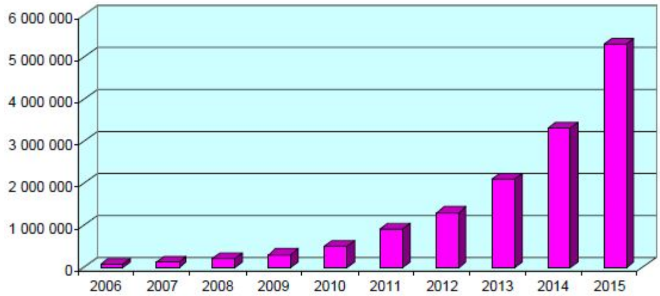

Figure 2.2: Example of the growth in mobile data usage in Gigabits per year. Represents a typical operator in a West-European country with a 60 million population [4]

In 2013, the need for LTE has changed slightly and is now driven by the exponential growth in mobile broadband data usage. This has been made possible by smart phones being introduced to mass markets and affordable broadband wireless services. As shown in figure 2.2 the mobile data usage is expected to increase intensively up to 2015 and is expected to increase further later on.

LTE introduces a new design for the radio access network and system architecture compared to 2nd and 3rd Generation networks (2G and 3G). The system architecture is based on the Internet Protocol (IP) and is therefore designed to support packet-based information. Figure 2.3 shows a simplified illustration of the LTE system architecture. The two main components are the Evolved Universal Terrestrial Radio Access Network (E-UTRAN), which consists of eNodeBs, and the Evolved Packet Core (EPC), which consists of the Mobility Management Entity (MME), the Serving Gateway (S-GW) and the Packet Data Network Gateway (P-GW).

The general architecture is similar to GSM and UMTS, but the number of logical network nodes is lower and thereby reduce cost and latency. With this simplified architecture testing has been shown that LTE can reach average speeds of approximately 20 Mb/s in urban areas in Norway [6], while at the same time offer-

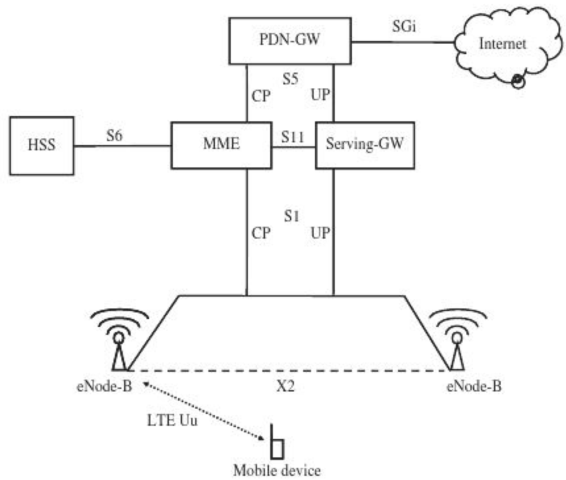

Figure 2.3: Overview of LTE Architecture. [5]

ing improved mobility and increased spectrum flexibility. This is valuable for Jernbaneverket, which has a limited frequency band and need all the capacity it can get.

However, LTE lacks some of the extra railway-specific functionality you get in GSM-R and this has to be solved. This can be done either through an LTE for rail (LTE-R) add-on or by adding the needed features to the LTE standard directly. There is a research project under way that will look into this issue. The Tecrail project is investigating applications that can be utilized with LTE and may give further advances for LTE as a replacement for GSM-R. [7] In addition LTE introduces a separation of layers, which is a crucial advantage over GSM-R. This means one layer can be changed without affection the function of another. Therefore, it seems likely that the solution will be to look at the LTE network as a transmission network that offers a data pipe. Everything else in the network will then be services that run between a server and a terminal. The only focus will be on the physical and application layer, leaving the link, IP and transport layer to be handled by normal standards. Applications would be implemented on dedicated servers in the application layer and not as services in the network itself, which is the case for GSM-R. The resources in the network could then be allocated based on critical and non-critical usage and be viewed as virtual networks that do not interfere with each other. [8] [9] How LTE can get these features will also be discussed further later on in the thesis.

Another issue with the potential shift to LTE is that it has a major impact on the mobile backhaul. To support LTE the backhaul has to increase its capacity and must support IP and Multiprotocol label Switching (MPLS) with packet-based networking. The IP and MPLS then becomes the common framework for services and operations in the network. Fortunately, Jernbaneverket already has support for IP/MPLS [10] and should therefore focus on increasing the capacity to support a future LTE implementation.

In addition there are challenges concerning regular voice calls. The LTE standard is all-IP and therefore only supports packet switching. Whenever voice calls are done to 2G and 3G networks from an LTE network this creates a problem, since voice calls coming from the LTE network can not be processed by the circuit switched 2G and 3G networks. This would also cause an issue for GSM-R and if an LTE network were to co-exist together with a GSM-R network it would have to be addressed. The problem could either be solved through voice Over LTE (VoLTE), Circuit switched fallback (CSFB) or simultaneous Voice and LTE (SVLTE). [11] With VoLTE an IP Multimedia SubSystem (IMS) is required, which can be quite expensive. It would, however, solve the problem no matter the scenario. With CSFB LTE would just be used for data services in a migration phase and whenever a call is initiated it would fall back to the GSM-R network. SVLTE requires a specific handset that can handle both technologies at the same time and could also prove to be expensive. These issues will be discussed further when each possible scenario is studied.

3 Conditions for a Future LTE Network

The future implementation of LTE in Jernbaneverket's network is dependent on several conditions and factors, both simple and complex, which makes a near future implementation of LTE both more and less likely. It is therefore natural to look at these conditions before the different scenarios are discussed later.

The complexity of the conditions is increased when you consider the size of Jernbaneverket as a company, the varying challenges it faces and the legal obligations it is given by the government. In addition there are several very different scenarios that all can end up bringing LTE to Jernbaneverket. These scenarios also have different conditions that affect the possibility of a future LTE network. Hence, this chapter considers only the general conditions, while specific ones for each scenario are considered later.

First of all the incentives for Jernbaneverket to upgrade can be simplified and mainly cut down to five. If LTE is to be considered as a reasonable upgrade it should give added value in these areas:

Improved Safety

Safety is one of the fundamental challenges for railway operations. Companies in the sector therefore all try to provide a safe and secure experience for passengers at all points of their journey. In addition it is also about protecting staff and owned property from crime, trespassing, vandalism and terrorism. The attacks on trains in Madrid in 2004, London in 2005 and Mumbai in 2008 have highlighted the vulnerability of rail transport to act of terrorism. Rail networks for passengers are open systems that are accessible through many entry and exit points and security measures therefore need to reflect these unique operational considerations without compromising the functionality of the vital infrastructure. [12]

Jernbaneverket's telecommunication network is also affected by the requirements and safety always comes first. Consequently, it should be emphasized how much this influences all operations Jernbaneverket undergo when dealing with its network. It is all about reliability and quality of service with redundancy. The network is responsible for crucial functions and a breakdown in the system could lead to a serious accident. Therefore, if LTE could show that it would improve the safety in several aspects of Jernbaneverket's core operations it could be implemented in the near future.

The Socio-Economic Factor

Being a state agency the socio-economic factor is something Jernbaneverket has to consider when planning, upgrading and developing its property. A new tunnel, bridge or railway will not be built by Jernbaneverket if they cannot calculate the socio-economic factor to be positive. This also relates to a potential network upgrade to LTE and if it could be shown that LTE would give socio-economic benefits an LTE implementation would become much more likely. These socio-economic benefits could come through improved safety and improved efficiency, but also through improved broadband on-board trains for example. However, these socio-economic analyses have shown to be susceptible depending on who does them [13] and there will therefore probably be much speculation and discussion on future analysis done on LTE as well. A socio-economic analysis will always have assumptions and the calculation will never be 100% precise.

Improved Efficiency

Rail transport operators and railway maintenance companies are increasingly judged on reliability and punctuality of their rolling stock and railway tracks. Travel time, frequency of departures and punctuality all are vital for rail operators to produce profit. In Norway, where Jernbaneverket is responsible for the infrastructure and railway operators are responsible for the rolling stock, the focus is somewhat different between them. Jernbaneverket has additional focus on the wayside infrastructure to give a good foundation for the rail operators. Information systems are vital for a more efficient railway that delivers value for money and LTE should therefore aim to give added functionality in both infrastructure and rolling stock relations, thereby increasing the likelihood of an implementation.

Cost Savings

Since Jernbaneverket is a state agency, costs and profit are not the main priorities. Jernbaneverket cannot create revenue higher than the production cost [8] and they receive a budget from the Royal Norwegian Ministry of Transportation and Communications (Samferdselsdepartementet in Norwegian). The focus is therefore on saving money instead of making money.

Jernbaneverket's GSM-R network fulfills its duties today, but allowing it to continue in the long run without an upgrade will over time increase cost, reduce efficiency and weaken customer service. A replacement of this through new technology should on the other hand generate improved value for money. [14] LTE must therefore show that it is a new technology that gives cost savings in the railway sector if implemented, but a business plan introducing extra revenue is not required.

Reduce the Carbon Footprint

Rail is an energy intensive industry, where 80 to 90% of the energy used is for traction purposes. [15] This is hard for LTE to influence directly, but the remaining 10-20% of energy consumption comes from stations, depots, control centers, signalling, communications and other rail systems. Here the signalling and communication could reduce its carbon footprint through the use of LTE. Since LTE is self-healing, self-optimizing and self-configuring it should use less energy than GSM-R. In addition LTE could decrease the energy usage in other areas indirectly by improving the efficiency of the railway. In the future the total energy consumption will increase even further to accommodate passenger and freight growth. The railway industry should therefore focus on operating in an energy efficient way and LTE can contribute to this.

The safety, efficiency and cost aspects are all big challenges that will be further described in the next chapter where it is shown that LTE give improvements. Even though these improvements make it more likely that LTE will be implemented it is not certain that it will happen. There will always be internal and external conditions influencing the final decision.

One factor is the high security requirement to the network. As mentioned earlier, the network is all about reliability and quality of service with redundancy. This increases the challenge of implementing a new network. A new network would most likely take longer time and cost more than it would for a commercial operator.

Another important factor is the complexity of Jernbaneverket's organization. The top management has varying responsibilities and challenges and the telecommunication network is just one small part of the big picture. The main focus lies on expanding and improving the railways directly, thereby reducing travel time and improving efficiency. It seems probable that they lack the overview to see that an improved telecommunication network

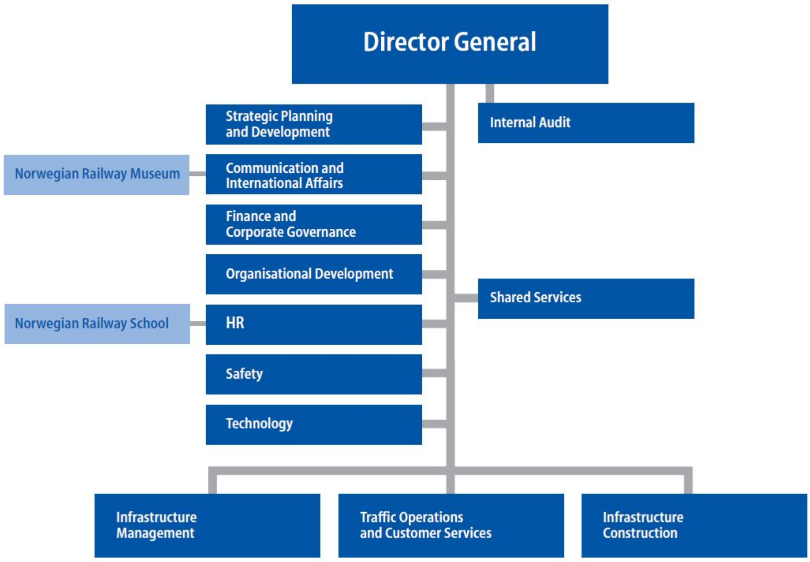

Figure 3.1: Overview of Jernbaneverket's organization. [16]

could give indirect benefits through techniques shown in the next chapter. Instead they focus too much on the physical part of the railway and ignore the possible exploitation of new technology that introduce intelligent techniques that lower cost, increase efficiency and improve security. These techniques require higher bandwidth and are not possible, atleast in large scale, with GSM-R. This challenge is something that Jernbaneverket should address and it will definitely affect the implementation promptness of LTE.

A factor linked to the organizational structure of Jernbaneverket is the willingness to upgrade the network. Within such a big organization there will be separations which hinder implementation of new technology. The same network is likely used by different groups within an organization and some of these might give resistance to change due to organizational or historical reasons. Scepticism towards sharing infrastructure despite cost savings is also likely. [9]

The willingness to upgrade is also linked to the way the railways are organized in Norway where you have NSB and Jernbaneverket as two distinct companies. While both are owned by the state only NSB are concerned with income. This introduces a peculiar situation with Jernbaneverket's telecommunication network, since NSB is very interested in offering broadband on-board to customers to improve customer convenience and thereby improve income. If this should be done through Jernbaneverket's network an upgrade would be required, since GSM-R is not sufficient. However, the telecommunication network is not owned by them and they can only affect the decisions regarding the network through communication with Jernbaneverket. NSB have tried to solve this issue through cooperation with commercial operators, but this has not proved satisfactory as of yet. [17] [18] Today, NSB use Jernbaneverket's network actively for internal signalling and communication. A natural solution could therefore be that NSB used Jernbaneverket's network for broadband on-board. Unfortunately, customer convenience is not Jernbaneverket's responsibility and it is not a valid incentive for it to upgrade the network. This factor would hinder an implementation of LTE unless Jernbaneverket understood how important NSB is for its operations as well. What benefits Norwegian rail operators, where NSB is the biggest, will often benefit Jernbaneverket and the whole Norwegian rail industry as well. If Jernbaneverket introduced an LTE network that NSB could use, this would increase the number of users utilizing trains. This could increase the socio-economic factor and would be beneficial for Jernbaneverket as well. We will therefore partly include NSB in the analysis in the next chapter. A positive aspect to this is that Jernbaneverket and NSB were one agency until 1996. There should therefore be a good cooperation environment between the companies.

In addition a condition that must be considered is the government support. Since Jernbaneverket is a state agency the budget is given directly by the government and many projects are directly dependent on the resources Jernbaneverket receives. This also affects LTE, which would require a part of that budget. When this fact is considered with the earlier mentioned lack of focus from the top management this makes a near future LTE implementation unlikely. However, the Norwegian government has allocated large resources to Jernbaneverket and Norwegian railways the last few years and it is an area that is receiving high support also for the next few years at least. Nonetheless, it is important that this government support is maintained and not abruptly stopped in the near future. This factor also supports the idea of NSB being important for Jernbaneverket. If the efforts and focus that exist right now on railway are shown to be successful and give better railways, while improving the competitive ability of NSB, it would also be positive for Jernbaneverket.

Something else to consider is the 3GPP standardization work and UIC/EIRENE standardization work. The LTE and LTE advanced standards are finalized, but there are proposals to add more functionality. [19] However, the present standard cannot be directly transferred to railway. It would still require some modification and UIC in cooperation with EIRENE and the other relevant railway organizations have to find a proper solution to this. With GSM they added extra functionality and called it GSM for rail, GSM-R, as explained in the background chapter. So far the indication is that UIC will try a different approach with LTE and try to get as much functionality in to the regular LTE standard, thereby not needing to add extra specific functionality for railway. [20] Whether this will happen or not will definitely affect the probability of an LTE standard. Unfortunately, the railway segment is too small to have a big influential role on the 3GPP standardization work and 3GPP has explicitly stated that a rail implementation of LTE is not in its focus. [8] [21] Luckily, there are some indications that LTE will end up with more functionality that is valuable to the railway industry than GSM did in its time. In the US, there is development of a public safety network based on LTE in the 700 MHz band. The US National Broadband Plan has allocated 5+5 MHz to public safety operations between 763 and 768 MHz and between 793 MHz and 798 MHz. This public safety network will be rolled out in July 2013 and have functionality similar to what rail communications need including group calling, addressing by function, rather than individual, and strict priority and pre-emption protocols. [22] It is therefore reasonable to hope that this public safety network could point the way for LTE as a replacement for GSM-R in the future.

The last condition that influences the future of LTE is the already existing GSM-R network. This network is not yet finished and development on it will continue for the next few years and it could take as much as 15 years before GSM-R is phased out completely. [8] It has a strong position in the European railway system and Jernbaneverket cannot simply remove it and start with LTE. GSM-R is a European cooperation and it must therefore be phased out in cooperation with others. It is in other words very unlikely that Jernbaneverket would introduce a new LTE network before the GSM-R network changes from a development phase to a maintenance phase at least. A future LTE network is therefore dependent on a GSM-R network to be at least partly successfully deployed and finalized before it can be introduced.

4

Incentives for a Future LTE Network

In the future, or even now, simple voice and constraint data services cannot satisfy high-speed data requirements from neither passengers nor railway companies such as Jernbaneverket. A next generation network (NGN) that improve train operational safety and on board safety and at the same time support broadband services will be required. LTE is a major upgrade compared to GSM-R in terms of bandwidth and speed and this difference ensures that LTE can be introduced for varying applications in Jernbaneverket's core operations. Jernbaneverket is aware of the next generation networks and know about the added benefits through broadband on board trains. However, Jernbaneverket's main view on a NGN right now seems to be that it offers new services that are nice to have and are outside Jernbaneverket's primary focus area, not offering any real improvements to its operations. This chapter may therefore provide some contrary evidence to this.

LTE offers prospects of lower maintenance costs and less downtime. It is also capable of providing improved and more efficient transmission in tunnels that will enhance railway operations management as well as customer service. Real time information could be made available both for Jernbaneverket and for its customers improving the flexibility when disruptions occur. Through innovation with LTE railway companies could deliver a modern, reliable and constant voice and data service supporting passengers as well internal operations. All in all, the UK's rail authorities

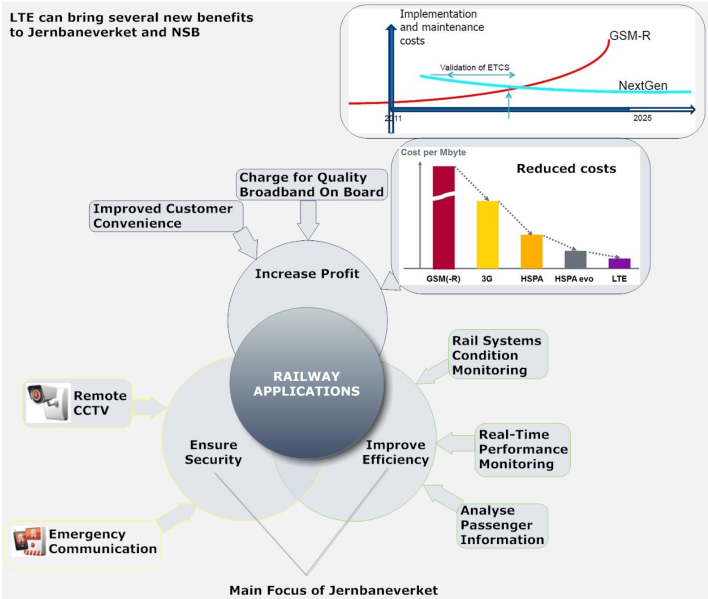

Figure 4.1: LTE Applications. [21] [22] [23] [24]

have identified up to 55 operational applications which could be run on LTE, ranging from mobile ticketing to traffic management and driver advisory systems. [25] There are in other words many possibilities with LTE. Some applications bring investment opportunities, while others bring expenditure reductions. Especially cost savings have many possibilities, but there could be several benefits for the efficiency and security aspects as well. For LTE to be considered as a future telecommunication network solution it must show its value in these areas.

NSB and Jernbaneverket have a common history and what is beneficial for NSB will in the end be beneficial for Jernbaneverket as well. Therefore, improvements and opportunities for NSB have also been considered. Below, examples of new applications that can be introduced with LTE are presented. It is also summarized in figure 4.1.

4.1 Ensure Security

Security is Jernbaneverket's main focus when considering the communication network. It must be reliable and have redundancy or a serious accident could happen and LTE must therefore show that is just as reliable as GSM-R. Additionally, security in general along the railway is naturally just as important and this is where LTE have true potential. LTE could improve existing alarm call services, the surveillance quality, swiftness of a diagnosis and information sharing in general. Jernbaneverket has also confirmed that an upgrade from GPRS and GSM-R is required if every train and station should have real-time video. [8] If the reliability and redundancy could stay equal at the same time as security was improved LTE would have a good cause.

4.1.1 Remote CCTV

Remote CCTV could introduce a multitude of new security applications for Jernbaneverket. [26] shows that moose and caribou are involved in several accidents each year. Flooding and avalanches are also a concern and this could be made more secure with CCTV solutions. CCTV cameras installed along a track would provide video feeds from crossings, platforms and hot spots where an accident is possible. A driver and control center could get video feeds showing the track a few kilometres in front of them for example. A system that warned when a car or lorry stalls on the level crossings could be added as well. If an incident occurred the remote CCTV would then give live access to recorded images. In addition integrated positioning of cameras can trigger recordings whenever activity is observed. The video analysis could also trigger automatic alarms and warn on-board staff or network controllers for example. When all this is transmitted and analysed in real time the situational awareness will be considerably increased and security is enhanced.

NSB has confirmed that they are very interested in getting CCTV on board trains. [27] In addition Jernbaneverket is interested in CCTV along railway crossings and areas with frequent accidents. [8] They should also be encouraged by the fact that a live CCTV feed are located on trains run by RATP in Paris. [28]

CCTV would definitely require an upgrade from GSM-R as the capacity is not able to manage the high data from the video feeds. LTE would be a natural choice for this. With greater capacity, LTE has the potential to revolutionize video surveillance by bringing live high-definition (HD) streams to hand-held devices used by security personnel, staff in control centres or directly to emergency services. This quality will improve zoom quality and replace grainy images associated with present CCTV applications.

4.1.2 Emergency Communication

Emergency Communication can be greatly enhanced by having video possibilities on trains. If there are fixed stations on board where you can communicate during emergencies this could enhance the response time and security. There are also examples of telemedicine being suggested in a railway context. [29] [30] This involves using audiovisual media for medical consulting and sometimes it can even be used to perform remote exams or procedures. This solution would therefore increase the accessibility of and to professional caregivers in remote areas under disasters or even if a customer experience general malaise during a train trip. This would require an upgrade from GSM-R, since it cannot handle HD video feeds and LTE would be a solution.

4.2 Improve Efficiency

Rail transport operators and railway maintenance companies must also focus on reliability and punctuality of their rolling stock and railway tracks. To find ways to improve the efficiency and availability is therefore important and LTE can play a part of this development. GSM-R and commercial solutions are used to improve efficiency already, but LTE gives further possibilities where the GSM-R capacity is not enough. Remote condition monitoring and advanced performance monitoring are two such areas. Just by applying remote condition monitoring and performance monitoring a UK rail operator is expecting 30% reduction in delay minutes, 20% reduction of cancellation and severe lateness, 10% reduction in man hours, 5% cost reduction in infrastructure and 5 to 7 % in energy savings. When the fact that 1 delay minute can cost up to £60 and 1 % energy saved is £100,000 saved (for a medium sized rail operator) this makes a future LTE implementation even more impressing. [21]

4.2.1 Rail Systems Condition Monitoring

Condition monitoring can significantly improve the performance and availability of the railway. It is already used with GSM-R, but with LTE this could be increased further with an increased level of detail in the monitoring. [31] Today, a great deal of the information regarding the equipment condition is only available when the trains are in the maintenance facility. [32] With GSM-R this has improved and is partly accessed remotely, but an upgrade to at least GPRS would be needed to reach close to real time data. [14] With LTE all of this information could be used to remotely monitor the conditions of the rolling stock assets and the infrastructure in true real time thereby reducing maintenance needed in general and also reduce the amount of unplanned maintenance. [23]

Machine-to-machine (M2M) technologies can be developed further with LTE to schedule maintenance in advance. [33] This network of machines and back-end applications would then communicate to monitor, control and collaborate on operations automatically. Research in the UK has shown that unplanned maintenance is very expensive and a reduction of this can save up to £130m per year. [34] Remote condition monitoring can contribute to this.

Examples of intelligent remote monitoring include the possibility to intelligently video monitor level crossings [32], monitoring the main transformer temperature [35], rock fall, bridge scour and flood monitoring [36], the usage of CCTV on cables [37] and many more. With LTE there is the possibility to upload all this to a centralized server where it can be monitored by specialised staff in true real time. [31]

The increased monitoring quality gained through LTE would in other words give added possibilities to condition based maintenance and increase the efficiency while at the same time lowering costs through preventive and predictive maintenance techniques.

4.2.2 Real-Time Performance Monitoring

Monitoring the performance of trains is interesting both for Jernbaneverket and train operators like NSB. Jernbaneverket wants the trains to pass as efficiently as possible, thereby reducing track load, and the train operators want punctual trains that run on time and as fast as possible. Accurate and real-time monitoring improves the quality on the traffic management by relaying the precise location of each train, the velocity, acceleration, braking capability, operational performance and other data necessary. This can be done with the existing ERTMS and GSM-R system today, but with LTE it could be improved to automatically give customers live information on train status. A broadband solution on board that provides information to passengers about the current journey and destination status would be highly valued according to research done in Belgium. [38] This information could include services such as platforms for specific connections and possible delays and links with other public transport services. This would then help passengers to identify the status of their train and connecting services. There is also a project called Mobilitet 2013 in Norway focusing on creating a shared platform for public transport. [39] Part of the aim of this project is to end up with a public transport system that share live information between each other and to the customers. This increased transparency and co-operation would increase the value of live information on board trains even further. A study has also shown that inadequate information from passenger information displays increases anxiety when trains are delayed. [40] Reducing this anxiety would make passengers more receptive to taking the train and LTE could contribute to this by enhancing the passenger information quality.

4.2.3 Analyse Passenger Information

By recording time and date information on passengers Jernbaneverket and NSB can use statistical analysis on the train load. By collecting information about travellers and their travel choices NSB could improve the planning and optimisation. It can also be used to inform passengers about the current or estimated load and improve customer convenience. Additional information about the cause of a disruption would also be beneficial.

This solution is actually done in a small scale by NSB already, but they use a commercial solutions and it is done through infrared on the doors of local trains. [27] The goal is to have 25 percent of the trains covered and with an LTE network owned by Jernbaneverket this could easily reached. It could also improve the quality of the system.

4.3 Increase Profit

Although increasing the profit is not a priority for Jernbaneverket, it is part of the bigger picture. It is also important for NSB and it should therefore be have some influence on Jernbaneverket. If the efforts and focus that exist right now on railway are shown to be successful and give better railways, while improving the competitive ability of NSB, it would also be positive for Jernbaneverket. However, for Jernbaneverket it would be about saving money instead of making money as they are not permitted to create revenue that is higher than the production cost. [8]

With LTE there are several possibilities for cutting costs as well and this is relevant for Jernbaneverket. LTE has a lower cost per Megabyte for operators with better performance and user experience and at the same time introduces several possibilities for creating profit. [24]

4.3.1 Improved Customer Convenience

Travelers today prefer a non-stop broadband internet experience and this is something NSB has tried to establish in cooperation with commercial operators. However, this has not worked satisfactory so far. [17] [18] One problem is that the commercial operators point the transceivers away from the railroad and towards the road traffic when they run parallel to each other. This is because the operators will get a much steadier usage from the road compared to the train where you will just have large peaks now and then for a few seconds. [8] A commercial operator is driven by potential revenue, population coverage and location coverage and it is therefore natural for them to point it towards the road. This is a problem that would disappear if Jernbaneverket gave NSB's customers access to a future LTE network, since Jernbaneverket naturally focus its transceivers towards the railway.

In addition trains generally have an advantage when considering convenience, since the journey can often be taken in one part compared to, for example, planes where you have several stops. This is something the railway industry really should try to exploit. Passengers do not want their personal or professional life to stop while they travel and trains with a stable working LTE connection would have a big advantage here. Working several hours uninterrupted on the train would often be better than an hour on a flight with only a few minutes at the laptop. LTE could also improve passenger information services, ticketing and seat reservation mechanisms and turn the journey into a truly enjoyable

Figure 4.2: Flight experience versus train experience. [41]

end-to-end experience. [23]

4.3.2 Charge for Quality Broadband On Board

NSB has proclaimed that broadband shall be free [27], but a premium broadband for Komfort-customers could be possible for example. Komfort users on board NSB trains pay an extra fee to get access to extra facilities and services such as electric power and free coffee, tea and newspapers. With a reserved quality broadband on board, Komfort-customers which have paid extra for their tickets could use Jernbaneverket's own stable network, while regular customers could use the existing commercial network. Through this freemium business model NSB (and Jernbaneverket) could satisfy the demands of business travellers and commuters using the train as a place to work. It would also increase the average ticket income for NSB as more people would use the Komfort seats.

In addition it would limit the load on a future LTE network and not require the same amount of frequencies to deliver a satisfactory result to the customers. The 4 MHz band used for GSM-R could be enough. A 2009 survey in Belgium concluded that on-board internet does not appeal to a mass market, but will attract a rather limited but heavily interested niche. [38] In addition the study showed that the willingness to pay for these services was quite low. However, the circumstances in Belgium are rather different than in Norway considering the difference in travel distances. Nonetheless, if part of these findings should represent the Norwegian situation this would support the freemium model, where the commuters would represent the niche. The train is a mobile office for many passengers and for companies and persons who charge by the hour, work on the train can often cover the cost of their fare. A survey in Sweden supported this view and showed that the train is widely considered an integral part of the working day. [42] This therefore suggests that rail services are more likely to appeal to business travellers if they are offered high quality broadband.

4.3.3 Reduced Costs

As mentioned before, LTE give several possibilities for saving money. First of all, with LTE Jernbaneverket have the option to deploy more M2M points compared to GSM-R and this would lead to better decision making thereby reducing costs. [43] For example the Swiss Federal Railways (SBB) is aiming to achieve up to 15 percent cost savings by 2017-2018 through more efficient technologies using machine-to-machine (M2M) solutions. [33] [23] The organizational structure of SBB includes both infrastructure and passenger traffic and it would therefore be reasonable to assume that Jernbaneverket could achieve substantial cost savings by attempting this as well.

LTE would also simplify the complexity of the existing systems. Jernbaneverket has already reduced this complexity drastically through its GSM-R system, but NSB should be very interested in replacing the commercial broadband solution with a proprietary Jernbaneverket LTE network. They would then use this network for both the signalling and internal communication as well as to-

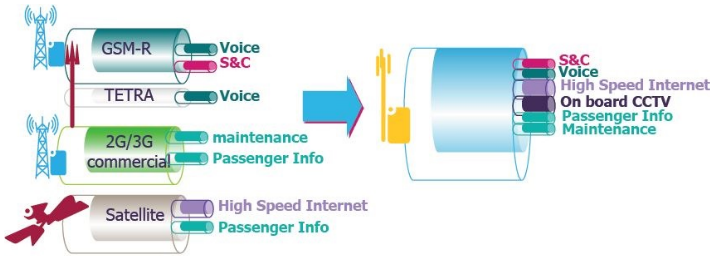

Figure 4.3: Single Standard System. [23]

wards customers, thereby reducing costs.

In addition if a national LTE network would be established the cost savings for the government would be even greater. Then each service in the different dedicated networks would be transferred to a single standard LTE system, as shown in figure 4.3. These services could then be run on its own server and in this way still stay separate, while saving costs and gaining access to improved network speeds. The different operators in this national LTE network could then share the network costs and would in addition be a powerful operator that could lobby with the regulators for the costs and availability of the needed spectrum.

Another vital opportunity is the lowered cost per Megabyte as shown in figure 4.4. This lowered cost for LTE derives from the network simplification, with flat IP architecture and enhanced capacity. [4] The rail industry could through LTE focus on the application and the physical layer and let the link, IP and transport layer be handled by normal standards. The EU project InteGRail has identified that systems using common standards can improve whole-system reliability by up to 50% by optimising maintenance and the cost of maintenance could be reduced by 10%, amongst other benefits. [15] On top of this LTE introduces the self-organizing network (SON) technology. A self-organizing network uses self-healing, self-optimization and self-configuration to improve the quality of the network, while at the same time lowering the cost. These networks automate preventive corrections,

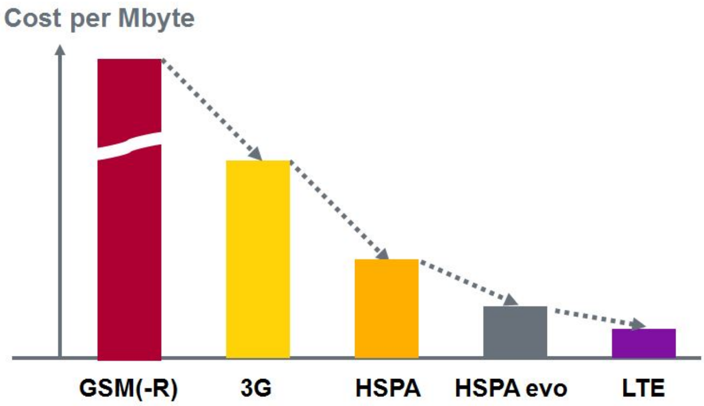

Figure 4.4: Cost Per Mbyte comparison. [24]

minimize revenue loss, uses the capacity optimally, maximises the revenue flow and create faster roll-outs for commercial operators. [41] Some of these functions should be useful for Jernbaneverket as well.

A final cost saving opportunity relates to the existing GSM-R network. GSM-R will be maintained until approximately 2025, where it reaches its end of life. [44] However, this system will have increasing implementation and maintenance costs up to that point. [23] Therefore, it is likely that a crossover point will be reached where it will be more expensive to maintenance the old system than to introduce a new next generation network, as shown in figure 4.5.

4.4 Additional incentives

Lastly, there are a few additional incentives for a future LTE implementation. The ERTMS system discussed in the background chapter is one of them. This system was originally designed for high speed lines, where relatively few trains appear in the same area at the same time. In these scenarios GSM-R has enough ca-

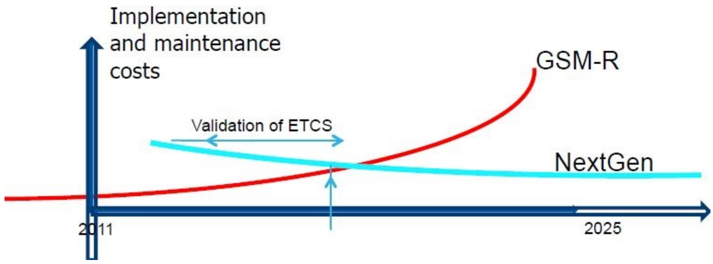

Figure 4.5: Maintenance cost of GSM-R. [23]

pacity. However, during congested or other abnormal situations GSM-R can be a limitation. GSM-R start to show clear shortcomings on large stations and marshalling yards with many moving units in a dense area, especially when it is combined with high volume of voice traffic from the staff working in the same area. If trains pass through at high speed at the same time the limitations are even worse. [45] [46] The limitations have also been visible in the ERTMS programme with a GSM-R bearer and a circuit switched connection. [44] Indications are that 15 onboard units using data cells are the limitation when they are using circuit switching.

Jernbaneverket is also testing out ERTMS at tracks in Østfold until 2014, but they are using circuit switching. The earliest time that ERTMS will be active in Norway is 2015 and they should find a solution to the limitations by then. One solution being looked at is adding GPRS to the GSM-R network and this will increase the capacity by a factor of seven. This will solve the problem in the short run. However, in the long run with a broader usage of ERTMS, GSM-R has to have a higher capacity than GPRS can give. [45] LTE would be the natural choice for this.

An issue also worth nothing is the spectrum efficiency. Efficient use of frequencies is very relevant for Jernbaneverket as the frequency band is limited to 4 MHz. LTE is far superior in terms of spectrum efficiency compared to GSM-R and give extra incentives for an upgrade.

Another problem is latency with GPRS. GPRS has a delay from 480 to 650 ms in Jernbaneverket's network. The round trip time then becomes very high with values up to 1400 ms. Although this is not optimal it is satisfactory for normal GPRS usage in Jernbaneverket's network. However, when location update on the SIM card is done there is extra latency with values reaching 3000 ms. This is so high that Jernbaneverket has disabled Centralized Traffic Control (CTC) in certain parts of the network, since CTC has a minimum requirement of 2600 ms. At Ofotenbanen for example it would be preferable to use this system, since there are long distances with old infrastructure being more faulty than elsewhere. [8] This could be solved with an upgrade to the backhaul and a NGN such as LTE.

5

Implementation Scenarios

As the last chapter showed, the emergence of LTE offers many exciting opportunities. LTE has the potential to transform passenger experience through individual journey plans, broadband on board and improved quality information during service disruptions. In addition it will give great benefits to railway companies. With LTE all communication can be made on a single platform and can therefore revolutionise the critical communication while optimising traffic and reducing costs. The high bandwidth will also be capable of supporting functions like VoIP, CCTV, platform and level crossing surveillance and railway signalling. With such fundamental changes on the horizon, railways must be ready to take advantage of the situation. However, given the slow moving nature of the railway industry and the amount of transformation required it will take time for Jernbaneverket to adapt to the most appropriate strategy. This chapter will look at three to four scenarios where such implementation strategies are discussed.

There are two essential components that rail companies need to consider if they are to realise the benefits of LTE. The first undertaking is to consider the capabilities of the access and transmission/core network. In today's solution Jernbaneverket has divided the core network into national, regional and access nodes. The national and regional nodes are required to have 10 Gigabit/s connections between each other and 1 Gigabit/s to the access nodes, while the access nodes are required to have 1 Gigabit/s between

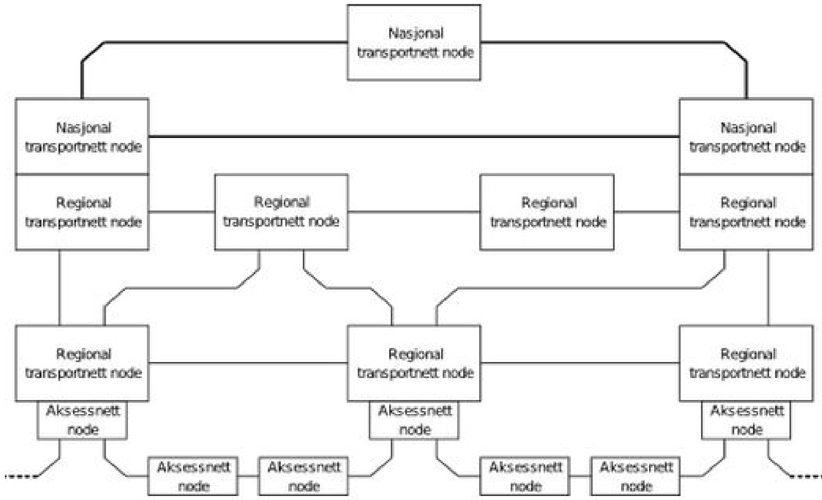

Figure 5.1: Overview of Jernbaneverket's network. [10]

each other and have a 2 Megabit/s interface in a ring structure, as shown in figure 5.1 and 5.2. [10]

A new private LTE network could have the same transmission core network with ring topology and redundancy, but have increased transmission rates to support the higher speed. Jernbaneverket already has support for IP/MPLS in this core network. This complements an LTE infrastructure and makes it easier to prepare for the evolution to high-bandwidth mission critical radio networks. [47] LTE is tailored to support any mix of critical and non-critical applications and is IP native, thereby making it possible to fully embed it with an IP/MPLS network. [48] Through this core network you get a separation of layers that gives higher flexibility and versatility. This is a crucial advantage of LTE over GSM-R, because it means one layer can be changed without affecting the function of another. [9] This avoids the need for a proprietary vertical standard and separate technologies can be used. New protocols can be added without affecting the rest of the interface. In other words the rail industry could through LTE focus on the ap-

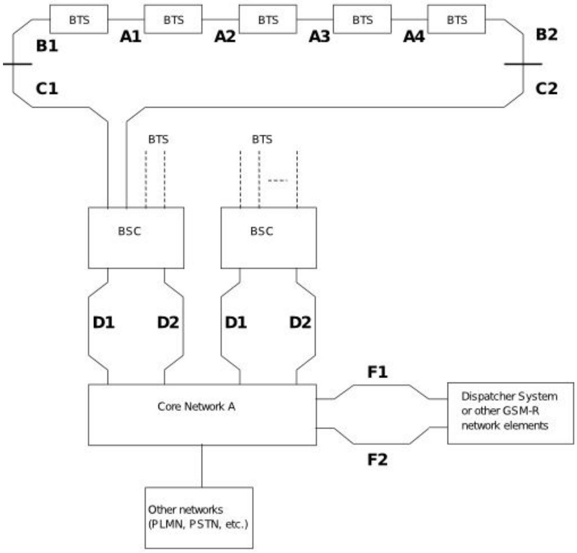

Figure 5.2: Ring Structure in Jernbaneverket's BSS network. [10]

plication and the physical layer and let the link, IP and transport layer be handled by normal standards. The EU project InteGRail has identified that systems using common standards can improve whole-system reliability by up to 50% by optimising maintenance and the cost of maintenance could be reduced by 10%, amongst other benefits. [15]

Jernbaneverket's network cannot accept a reduced quality of service or stability. Therefore a new LTE network should have an access network added in parallel to the existing one in a migration phase. The transmission and core network would also need an upgrade, but these would not need the same degree of parallelism. The standard cost for a new core network like this is very dependent on the number of clients and volume needed. The requirements for redundancy and availability (uptime) also affect the cost. A reasonable estimate is that a brand new LTE standard core network should cost minimum 12-15 million NOK and that this increases to about 25 million NOK when redundancy and availability is added. For Jernbaneverket there should be some changes to the core network, but large parts of the transmission and core network could be re-used, thereby reducing this cost significantly.

In addition there is the cost of implementing the access network for a second network. Since sites are re-used there would likely be substantial cost savings on the second network here as well. This is because radio towers, batteries and similar infrastructure are primarily the same when you use either one or two systems. However, the sites in the access network would need upgrades in hardware and transmission as well as new radio equipment. This cost varies, depending on how much that can be re-used, but a reasonable estimate is that the hardware upgrades and radio equipment would cost about 200 000 NOK per site. [49] In Jernbaneverket's existing network there are 525 base stations and this would amount to a total cost of approximately 105 million NOK. [50] On top of this the radio-relay would need to be upgraded to handle the increased transmission and a broad estimate is 20 000 NOK per site. [49] However, fibre might be an alternative to the improved radio-relays and Jernbaneverket has a goal of building fibre throughout the access network. [8] Whenever maintenance work is needed along the railway Jernbaneverket has a goal to put either pipes for fibre or fibre there. Unfortunately, it will take several years before the fibre is laid everywhere. For this reason there will still be upgrades required on the radio-relays, at least if LTE is added in the foreseeable future. There would also possibly be the additional costs of implementing antennas for LTE in the 110 tunnels that have radio coverage for GSM-R today. [50]

To sum up the capital expenditure will be approximately 105 million NOK for the new access network, plus additional costs for antennas in tunnels and improved radio relays or new fibre access. However, there is a plan to include fibre anyway and it should not affect the budget for a future LTE network too much. In addition the cost will be 25 million NOK for a brand new core network with upgraded transmission. Since the real cost will be noticeably lower than 25 million NOK for the core network, but probably higher for the access network, because of the tunnels and the upgraded radio relays or fibre, it is reasonable to calculate the total capital expenditure to approximately 130 million NOK. This estimate does not include the main cost of fibre, since some of this will be built regardless of LTE. [8]

Concerning the operating costs an estimate is that the second system would have costs between 25 to 50 percent of the first system. As mentioned, there would be re-usage of large parts of the transmission and core network. However, there would be more breakable components and more site visits for fault handling would be necessary. This would drive the costs up, but the operational cost of the second system would still be significantly less than the first. [49] Jernbaneverket has a budget of approximately 150 million NOK per year for investments and maintenance and the operational costs would increase to between 190 and 225 million NOK with LTE, where somewhere close to the lower number is the most probable result. [8]

Having considered the core and access network the second undertaking required is to consider the frequency and spectrum usage, and this is a key issue. Industry bodies, such as the European Railway Agency (ERA) and UIC, are working to secure spectrum allocation for rail use. [25] With GSM-R the industry gained available spectrum for free, but that is unfortunately unlikely to happen again. [9] Jernbaneverket therefore has to find alternative ways to get spectrum. The radio spectrum in Norway is available in some frequency bands and Jernbaneverket already has its own 4 MHz band where it uses GSM-R. There are auctions taking place in the 800 MHz, 900 MHz and 1800 MHz bands in December 2013 and this could give an opportunity for Jernbaneverket to get an alternate band. [51] However, the 800 MHz require a commitment to provide 98 % coverage within 5 years after the auction. Jernbaneverket should therefore be especially interested in the 900 MHz band, since it is adjacent to the existing GSM-R frequency band and has no limitations. However, this band will be expensive and Jernbaneverket will have no chance to compete with the commercial operators for this band. It is also late in the game and probably too late to start to think about bidding for this spectrum now. Luckily, there will be another opportunity in 2021 when the 700 MHz band is released from Norges televisjon (NTV). [52] This band will be highly valued by the different commercial operators and they will have the same strategy towards this band as they had towards the 800 and 900 MHz bands, where it now seems like the three big operators (Telenor, Netcom and Mobile Norway) will end up with all the capacity split between them. It is therefore important for Jernbaneverket (and other non-commercial operators such as Nødnettet) to start declaring an interest and lobbying for this already now. Hopefully, the 700 MHz band could then be partially available with restrictions given on parts of the frequency band opening up for services such as Nødnettet and Jernbaneverket in the auction. It is also possible that some of the frequencies might be given out, especially if a national LTE network became reality. The GSM-R network is already established in the 800/900 MHz band and an additional LTE network in the nearby band would be good for meeting moderate capacity requirements over wide areas. If an auction was the only option, the costs would also be high. A similar auction took place in the 800 MHz frequency band in Denmark last summer (2012) and the total cost of these frequencies ended up at 1 billion DKK. [53] This is way higher than what Jernbaneverket can afford through its budgets and resource allocations. The buying power of the commercial operators is simply superior. Therefore, it seems unlikely that Jernbaneverket will gain frequencies through an open auction, at least in the 700, 800 and 900 MHz bands.

If these two components are handled, LTE will likely be implemented in two steps. Non-safety critical applications that require broadband will be the only features utilized in the beginning, but these applications will drive the migration for safety-critical applications. When ERTMS and ETCS is standardised on IP networks it will become possible to validate LTE as a true replacement for GSM-R and a migration for safety-critical applications will also take place. This might seem like a distant prospect, but Jernbaneverket must start to prepare for it today. Understanding LTE and what it offers is the first step towards unlocking the benefits. [25]

How these problems should be tackled also depends on the different scenarios and it will therefore be discussed further in the specific scenarios below.

5.1 Build Its Own Parallel Network

One way to implement LTE is to build a new additional private network. It should be added gradually as a parallel system next to the existing one and be thoroughly tested before replacing the old GSM-R network. LTE is not compatible with GPRS and the frequencies would be a problem, since a dedicated frequency band is needed for the new LTE network.

Hence, with an implementation of LTE as a new additional private network there are two options. Jernbaneverket can either divide the 4 MHz band between GSM-R and LTE or they can try to get a new frequency band, either in an auction or through government distribution.

Both of these options will have the same challenges concerning interoperability with voice coming from the packet switched LTE network to the circuit switched GSM-R network. Therefore, a future LTE network in this scenario will most likely be limited to data transmission in the beginning, while using Circuit Switched Fallback (CSFB) whenever a voice call is made. Over time, as LTE establish itself as a data bearer for signalling systems, voice will be implemented through the IMS framework. It might even happen earlier, since many of the data functionalities could be introduced earlier through an IMS framework. It would then be natural to include voice in this.

	Helpful	Harmful
Internal	**Strengths** • No frequency band auction or lobbying needed • Technological Competence • Experience with a proprietary system • Site re-usage possible	**Weaknesses** • Frequency planning needed on both old and new network • Sacrifices bandwidth in a migration phase • Coexistence issues • Low LTE data rate • Security requirements • Profit not a high priority • Top management not focusing on telecommunication • Willingness to upgrade
External	**Opportunities** • Government support • Changes in government politics • LTE gaining new features	**Threats** • Changes in government politics • UIC Standardization changing direction

Table 5.1: SWOT table with own parallel network and divided frequency band

5.1.1 Divide the 4 MHz band between GSM-R and LTE

The first option avoids the problem of winning an auction or lobbying for government agreement. However, it brings new problems as well. A partitioning of the frequencies would require substantial frequency planning both on the existing GSM-R network and the new LTE network, since LTE is not compatible with GPRS and GSM. This partitioning would also limit the bandwidth of the GSM-R network and it is unclear whether ERMTS would function in GSM-R with so few frequencies. It would surely require GPRS in the network to limit the use of time slots with ERTMS at least. [46] A likely solution would be to have GSM-R in 2 MHz and LTE in approximately 1.4 MHz of the total band. However, an LTE network this close might give some interference to the GSM-R network. In addition such a narrow LTE frequency band would severely limit the LTE data rate and it would likely be below 2 Mbps in the migration phase and around 2 Mbps after migration. [21] This parallel system should therefore be ended as fast as possible. Such low data rates would also surely remove the commercial possibilities of broadband on board through Jernbaneverket's network for NSB, at least in the migration phase. However, it would still be good enough for internal usage and the security improvements, efficiency enhancements and cost reductions would still be valid. If the freemium model discussed earlier was used it could limit the load on the network and prove a satisfactory solution for Komfort-customers when GSM-R was phased out.

All these considerations are summarized in the SWOT table 5.1. In addition the general challenges and conditions mentioned earlier in chapter 3 have been added to the consideration. The SWOT model is also explained in the appendix.

	Helpful	Harmful
Internal	**Strengths** • Easiest to implement • Technological Competence • Experience with a proprietary system • Site re-usage possible in 700, 800 and 900 MHz band • No impact on the GSM-R network • High LTE bandwidth	**Weaknesses** • Willingness to upgrade • Security requirements • Profit not a high priority • Top management not focusing on telecommunication
External	**Opportunities** • Government support • Changes in government politics • LTE gaining new features	**Threats** • Not acquiring enough frequencies • Changes in government politics • UIC Standardization changing direction

Table 5.2: SWOT table with own parallel network and a new frequency band

5.1.2 New Frequency Band

This solution would be the easiest to implement, but has one big problem and that is getting the frequencies. If these could be acquired Jernbaneverket has the technological competence and experience with proprietary systems to easily implement a parallel LTE network and test this thoroughly before GSM-R was phased out. These extra frequencies, no longer needed by GSM-R, could then be used to offer customers on trains free quality broadband for example. However, the 900 MHz band opening up in the December 2013-auction is not reserved for any particular industry and Jernbaneverket would therefore have to bid in the auction coming up to get access. This auction is most likely going to be decided between the three big commercial operators and another possibility is therefore to agree a deal with one of the commercial operators and use their white spaces of frequencies, not used locally, along the railway. Also, a golden opportunity would be the 700 MHz band opening up in 2021. [52] There are still some years left and this gives Jernbaneverket time to prepare. In the US parts of the 700 MHz band have been reserved for LTE-based public safety systems and should give some positive signs to Jernbaneverket as well. If LTE was established in the 700, 800 or 900 MHz band this would also open up possibilities for site re-usage.

All these considerations are summarized in the SWOT table 5.2. In addition the general challenges and conditions mentioned earlier in chapter 3 have been added to the consideration.

5.2 Rent Access as a Mobile Virtual Network Operator

This solution involves Jernbaneverket becoming a mobile virtual network operator (MVNO) renting capacity of a commercial operator on its frequencies. The main benefit here is that very little capital expenditure is needed, since the commercial operator would be responsible for the coverage and infrastructure of the new network and an expensive frequency auction would be avoided. In theory Telenor, Netcom and also Mobile Norway (in the future) all will have above 98 percent coverage in Norway and should therefore be able to offer coverage to Jernbaneverket as well. At least, if they win a part each in the 800 MHz band auction taking place in December 2013. [51] This should indicate that Jernbaneverket can reach market price for these services by enquiring all three operators.

On the other hand the problems associated with this solution are severe and would most likely cause issues in some way. First of all the security and quality of service requirements will be much harder than what a commercial operator is used to. It might not even be possible for a commercial operator to deliver these requirements, and if they could the price might be very high. [47]

It is also unlikely that the selected operator would be willing to perform the necessary upgrades on the infrastructure without some kind of assurance that Jernbaneverket would use its solution for an agreeable period of time. This would create a very strong lock-in effect, not only through the contract, but also through increasing switching costs, since they become more and more dependent on the rented solution from a specific operator. Another problem is that Jernbaneverket has little experience as a MVNO and would prefer a proprietary solution similar to the one it has today. [8]

Finally, there are issues concerning ownership over sites and positioning of transceivers. The selected operator most likely have sites along the railway, but in rural areas they are often faced the wrong way, against the road instead of the railway and NSB has experienced problems with this. [17] [18] The reason for this is that statistical analysis of cells with transceivers pointed towards railways in rural areas will show little activity with major peaks now and then. This makes it hard to configure the transceivers specifically for railways and the transceivers are focused on

	Helpful	Harmful
Internal	**Strengths** • Not much capital expenditure needed • Technological Competence	**Weaknesses** • Little experience as a MVNO • Security requirements • JBV prefers proprietary solutions
External	**Opportunities** • Will reach market price through auction with Telenor, Netcom and Mobile Norway • Changes in government politics • LTE gaining new features	**Threats** • Not enough focus on QoS and redundancy • Less ownership over sites. • Costs can be considerable over time. Lock-in situation is probable

Table 5.3: SWOT table with Jernbaneverket as a MVNO

the roads instead, where you have lower peaks, but more average activity. To counter this Jernbaneverket could give access to its sites and let them place transceivers there, but this would require new frequency planning and Jernbaneverket would be required to take the costs.

If Jernbaneverket was to implement LTE as a MVNO they should therefore use the LTE network as a best effort network that is not to be trusted for crucial functions. It would not be possible to phase out GSM-R, since it would be required to do the crucial functions. LTE would just be used for a few functions and would therefore lose many of its incentives discussed earlier. It could not establish itself as a permanent solution either and would just be temporary.

All these considerations are summarized in the SWOT table 5.3. In addition the general challenges and conditions mentioned earlier in chapter 3 have been added to the consideration.

5.3 Cooperate and Build One National LTE Network

The final solution is the grandest one. It would involve several agencies and government departments cooperating on building one national LTE network. More specifically, it would be a partnership between important operations such as the paramedics, the police and the fire service together with Jernbaneverket. In addition agencies like The Norwegian Public Roads Administration (Statens vegvesen in Norwegian), Avinor, search and rescue, border control, the civil defence and the military as well as other public agencies could be interested.

In many ways it could be considered a dream scenario, since you would get a common platform for many operations and it would be a big network with a high degree of influence and power, which would give the system high government support. Many of the

	Helpful	Harmful
Internal	**Strengths** • Would create a strong network with influence and power • Jernbaneverket's Technological Competence • Socio-economical factors	**Weaknesses** • Willingness to upgrade • Security requirements • Have to share frequencies with others • Top management not focusing on telecommunication
External	**Opportunities** • Government support • Changes in government politics • LTE gaining new features • All parties involved will have focus on QoS and redundancy • TETRA for data purposes is outdated	**Threats** • Not acquiring enough frequencies • Changes in government politics. Who will take the costs? • UIC Standardization changing direction • Cooperating smoothly with all parties involved

Table 5.4: SWOT table with a National LTE Network

agencies also have similar requirements for redundancy and QoS as Jernbaneverket and the network would therefore be built with this in mind. It could become a perspicuous network cooperation that would be easy to govern and could give substantial cost savings and increase the efficiency of each agency. Many of the mentioned incentives targeted on Jernbaneverket's situation could be applied to the different agencies as well. On top of this the socio-economic factors could really contribute.

One factor that lessens the enthusiasm for this solution is that there already exists a public safety network called The Norwegian Public Safety Radio (Nødnett in Norwegian) for the paramedics, the police and the fire service. This is based on Terrestrial Trunked Radio (TETRA) technology, which shares some of the capabilities and requirements of the GSM-R system. Public safety users are an important community both economically and socially, but their market is much smaller than for commercial users. Therefore they cannot attract the same level of investment as the commercial cellular networks, much like Jernbaneverket.

Luckily for this scenario, it is in many ways outdated when it comes to data transfer and the TETRA organization is positive to an upgrade to LTE. [54] A hybrid solution being considered is to keep the TETRA technology for critical signalling and implementing LTE for transfer of images and video. [55] This was also discussed as a solution with GSM-R for Jernbaneverket in the other scenarios as well. A hybrid solution would increase the costs for a Nødnett project that is already over budget and the top management in Nødnettet has been positive towards some kind of cooperation where frequency sharing is established. [52] Their idea has been towards the commercial operators, but a frequency sharing scenario with other non-commercial operators such as Jernbaneverket should be just as easy.

Establishing a common technical standard for commercial cellular operators and public safety operators would offer advantages for both and it is just a question of time before the Norwegian TETRA solution would need an upgrade. If a common technical standard, such as LTE, were established this would give two benefits. The public safety operators would gain access to the economic and technical advantages generated by the scale of commercial cellular networks and at the same time the commercial cellular operators would get the opportunity to address parts of the public safety market. It will in other words lead to a competitive equipment market. [56] This is probably part of the reason for the LTE initiative created in the US on the public safety 700 MHz band. The competitive equipment market would also benefit Jernbaneverket, regardless of what way LTE is introduced. Still, whether this upgrade will happen with the Norwegian Nødnett in the near future or at a later point is too early to say. On the other hand, the release of the 700 MHz band from NTV in 2021 seems like a promising opportunity both for Jernbaneverket and Nødnettet to implement LTE and time will show if they will do it together or alone.

Getting enough frequencies to cover all agencies involved is a big problem for this scenario. In the case where cooperation is established and government support is given there would be frequencies available from the respective agencies, but in a migration phase they would still need them to function. A partitioning of all the frequencies in the different agencies during the migration phase, as proposed in scenario 1, would most likely be too complicated and expensive. Therefore, the only solution would be to acquire frequencies through auctions or government allocation. The most realistic and first possibility for this would be the 700 MHz band in 2021. It is therefore important that the Norwegian Post and Telecommunications Authority (Post- og Teletilsynet (PT) in Norwegian) reserve part of this band towards this solution and not uncritically puts them out on an auction like they did with the 800 and 900 MHz band. The World Radio Conference in 2015 will also be important. [57] If a national LTE network became a reality it would also have government support and it would make sense to allocate part of the 700 MHz band to this. A final note is that if part of the band is reserved and the migration phase gets done the respective frequencies from each agency could also be freed later on.

Another problem is that cooperation is not always easy and in this scenario you would have many agencies with somewhat different agendas. There is also the practical implementation of the system and how the costs should be divided between the agencies and the government in the migration phase. On a more detailed level there would be several problems that definitely would pop up for such a big project.

What separates this scenario from the others is that it is more or less outside of Jernbaneverket's control. It depends on several factors that have little or nothing to do with Jernbaneverket and its management and it is therefore hard to predict whether this is likely to happen in the future or not.

Finally, it is worth noting that this scenario will have several agencies involved and establishing a common IMS framework might be required for the solution to function. Therefore, it would not be necessary to use CSFB and VoLTE could be implemented relatively early after a national LTE network became reality.

All these considerations are summarized in the SWOT table 5.4. In addition the general challenges and conditions mentioned earlier in chapter 3 have been added to the consideration.

5.4 Discussion and Results

For LTE to meet the requirements, concerning both safety critical and non-safety critical functions, Jernbaneverket must overcome technical, regulatory and commercial obstacles. It took eight years to build the GSM-R standard and it will no doubt take time to establish LTE as a reliable railway standard. Therefore, a parallel utilization where LTE operate in tandem with GSM-R is the most feasible solution. Jernbaneverket could then benefit from LTE in small scale within five years, together with customers (rail operators and their passengers). The reward from thereon is potentially enormous and Jernbaneverket got much to earn on being in the lead in this development. [58] Only 11 percent of the capacity is needed for operational use and 89 percent is driven by passenger demand. [59] Introducing a stable LTE network early on and then implementing more and more functions for operational use would therefore greatly benefit not only NSB, but also Jernbaneverket and the Norwegian rail industry as a whole. This is particularly true if users are paying for quality broadband through Komfort-tickets or see it as an important reason for choosing rail travel. It would be challenging to meet customers' expectations, but through a long and smooth upgrade period there would be increased flexibility and investment savings for Jernbaneverket and an increase in passengers for NSB. In other words, LTE would initially be used for innovative applications that are operational, passenger, or safety-related, but as we approach 2025 LTE will be capable of acting as a data bearer for future signalling systems.

There is no denying that implementing a LTE network would bring substantial costs. An estimate of 130 million NOK in capital expenditure and an increase of between 40-75 million NOK in operational expenditure during the migration phase are large sums when you consider that the existing yearly budget is at 150 million NOK. However, the different applications and their benefits have already been discussed in detail and the railway suppliers indicate that the advantages of the new applications accessed through LTE definitely outweigh the cost implications. [47] After the migration phase is over, there are several indications that LTE will have lower operational expenditures. [15] [23] [41] In addition there are numerous examples of applications lowering total costs indirectly through LTE. [14] [21] [23] [31] [32] [33] [35] [36] [37] [43] When this fact is combined with the different benefits for security and efficiency there should be little uncertainty concerning LTE doing an excellent job as a future telecommunication network for the railway sector. It seems highly probable that this is the case for Jernbaneverket as well.

Having introduced different scenarios for a future LTE implementation there are a few aspects that needs to be discussed. First of all, the scenario with Jernbaneverket as a MVNO should be discarded. The scenario has several flaws, where the most crucial flaw is the security and quality of service aspect. The transition to wireless multi-service networks means it is increasingly important for rail operators to ensure they are self-sufficient in network coverage. The commercial operators will not have financial reasons to offer the required quality of service and Jernbaneverket would have to subsidize these investments. [47] Instead of subsidizing another operator it would make more sense to create a proprietary network, since Jernbaneverket got the technical competence required. Another possibility is to use the commercial operator's network as a best effort network. However, if Jernbaneverket decided to do this instead it would not be possible to phase out GSM-R and there would be very few incentives for LTE left. It would only leave behind nice to have-features. On top of this the solution is not recommended by commercial producers and Jernbaneverket would prefer a proprietary solution. [8]

All these aspects leave two main scenarios for a future LTE implementation, either a national LTE network or a proprietary parallel network. Both of these solutions are influenced by the conditions and factors discussed earlier and are summarized in the SWOT tables. A national LTE network would be the best long term solution for the government, but if it is the best solution for Jernbaneverket is discussable. In addition it is outside of Jernbaneverket's control and includes a lot of speculation and assumptions. Nonetheless, frequency sharing is an increasing trend in the commercial part of the telecommunication world today and it is a scenario with exciting prospects. And why should there be built dedicated and separate networks for each area? Cooperation makes sense when you consider the size of Norway in connection with the low population. Nødnettet, GSM-R, at least three commercial networks and a lot of local operators all using their own frequencies create over-investment, poor frequency utilization and increased operating expenses. If LTE became a common base for many of these networks the idea could be to establish virtual networks on a common infrastructure with full control on QoS for each participant in the telecommunication network. All the different applications handled through the application layer could be realized through IMS and the different operators would split the cost on establishing it. Telenor and Tele2 are frequency sharing in Sweden and Telenor and Telia are doing the same in Denmark. Namely, there are established routines for how this can be done and Jernbaneverket, Nødnettet and others should seriously consider it as a possibility. They should start discussing it soon and not wait, though, if they want to have a plan ready for 2021 or at least 2025.

Finally, there is no doubt that building its own parallel network and gradually migrating traffic and applications is Jernbaneverket's natural favourite choice. If this should be done through a new frequency spectrum or through a partitioning of the existing frequency band is an important question.

A crucial point is that the migration phase could not be ended in the near future even though LTE was introduced in the next few years. The reason for this is ERTMS. It is based on GSM-R and it would take several years before it was standardized on LTE. If ERTMS became standardized for LTE it would still take additional years before GSM-R could be removed, since roaming trains in Norway travelling from EU could still be equipped with GSM-R-only equipment. Even though Jernbaneverket would be future oriented and implement LTE early this means that they are required to run GSM-R in parallel until at least 2025, when support to GSM-R from suppliers stops. [20] Ironically, this means that a European cooperation could somewhat delay a future next generation network. Especially the scenario with a partitioned frequency band suffer from this fact, since an early LTE implementation would demand a long migration phase with far from ideal bandwidth both for GSM-R and LTE. The partitioned frequency scenario is therefore unlikely for a near future implementation of LTE, but would become more and more probable as the world advances towards year 2025.

To sum up there is only one viable solution for a near future implementation of LTE: To build a parallel network on a new frequency band. However, Jernbaneverket is less enthusiastic than NSB to a fast implementation. The reasons for this are mentioned earlier and include the top management not focusing on the telecommunication network and the fact that it is not driven by revenue and customer convenience. Jernbaneverket doesn't need to implement LTE in the near future, since GPRS is enough for ERTMS and other data needs they have at the moment. This reduces the motivation to implement LTE soon and it is more likely that it will be implemented at a later point.

If LTE is implemented at a later point close to 2025 there are two likely solutions. Either the same as for near future, but now including frequency partitioning as well, or a national LTE network. It has been explained that a national LTE network is dependent on several external factors and the relevant participants must start to work together soon. There are no clear indications towards this right now. The best guess for a future LTE network for Jernbaneverket would therefore be that it will start up with a proprietary solution close to, but hopefully before, 2025. A parallel LTE network gained in 2021 on a separate 700 MHz frequency band should be the primary goal.

6

Conclusion and Future Work

LTE is a promising new wireless communication standard that vastly outperforms the existing GSM-R solution that Jernbaneverket uses today. LTE can be used for a number of new applications and the potential for further applications through LTE are enormous. Specifically, this thesis has identified applications that could ensure security, improve efficiency and reduce costs or increase profit for both Jernbaneverket and rail operators. In addition UK's rail authorities have identified up to 55 operational applications which could be run on LTE.

Any upgrade from GSM-R to LTE will take time and there is no doubt that investments are needed. Fundamental changes must be carried through and given the slow moving nature of the railway industry Jernbaneverket must start preparing now, so that it is ready technically, regulatory and commercially to take advantage of LTE when it becomes relevant.

Therefore, Jernbaneverket should look at the internal weaknesses, external opportunities and external threats affecting a future implementation scenario for LTE. This includes the high security requirements, top management not focusing on telecommunication, the willingness to upgrade, the lack of priority on profit and cost savings, the importance of government support and potential changes in this and lastly future additions to LTE features,.

In addition there are two essential components Jernbaneverket must consider to be ready technically. First of all, Jernbaneverket must upgrade the transmission network. With IP/MPLS support already in place, all that is needed is an upgrade to the capacity. Secondly, a key issue that must be resolved is the frequency. Even though the industry gained frequency spectrum for GSM-R for free this is unlikely to happen again, at least by itself. Consequently, Jernbaneverket has to find alternative ways to get the needed frequency spectrum. There are auctions taking place in the 800, 900 and 1800 MHz band in December 2013 and this would be the first opportunity. However, it is probably too late to start to think about bidding for this spectrum now. In addition, Jernbaneverket's most favourable 900 MHz band has not been given any requirements from Post- og Teletilsynet and is therefore up for grabs for the commercial operators and they most likely will end up dividing the frequencies between them. Luckily, there will be another opportunity in 2021 in the 700 MHz band. This band will also be highly valued by the commercial operators, and it is therefore important that Jernbaneverket and other non-commercial operators start declaring an interest and lobbies for access to this frequency spectrum already now. Hopefully, this band could then get restrictions on some frequencies giving Jernbaneverket the opportunity to access them.

All this require investments and it is estimated that a brand new core network would cost 25 million NOK. Luckily, large parts of the transmission and core network could be re-used ending up with substantial savings on this cost. However, the access network will be new and LTE will demand an upgrade on the radio relays at the base stations. Even though sites are re-used it will still be costly and it is estimated that the cost will be approximately 200 000 NOK per base station. Jernbaneverket has 525 base stations and the total cost therefore becomes an estimated 105 million NOK. A capital expenditure of roughly 20 000 NOK must also be added per relay point upgrade. However, this last cost can be avoided if fibre is installed already. On top of this there are 110 tunnels with antennas installed for GSM-R and these might require an upgrade for LTE as well. The total capital expenditure therefore becomes somewhere around a broadly estimated 130 million NOK. In addition the operational cost will increase with 25 to 40 % in the migration phase and be between 190 and 225 million NOK. Nonetheless, there seems to be broad consensus between the railway suppliers that the opportunities LTE bring definitely outweigh the cost implications. As this thesis has shown it seems highly probable that this is the case for Jernbaneverket as well.

Of the three different implementation scenarios presented in this thesis the scenario with Jernbaneverket functioning as a MVNO should be discarded. The scenario merely removes too many of the vital incentives Jernbaneverket has to upgrade to LTE. Therefore, there are two main scenarios. For a near future implementation a parallel network on a new frequency band is the only applicable solution, at least if Jernbaneverket wants to include all the incentives discussed in this thesis. There are no clear candidates for this frequency band right now and an implementation at a later point seems more likely. If LTE is implemented at a point close to 2025 there are two likely solutions. Either the same as for near future, but now including frequency partitioning as well, or a national LTE network. At the current point in time there are no clear indications that a national LTE network will be established and a proprietary implementation between 2021 and 2025 in the 700 MHz band therefore seems most promising.

Future work may involve looking further at UIC reviews concerning LTE and see how the outcome affects the future of LTE for rail. LTE compatibility with ERTMS is also possible to study. Another opportunity is to look deeper at different ways LTE can be implemented for Jernbaneverket. For example by means of frequency sharing not only with the Nødnettet, but also with Ice.net or other commercial operators. In addition a focus on finding more applications that can be introduced with LTE is reasonable or there is the possibility to go in depth on one or a few of them. Especially possibilities with a stable broadband on board could be discussed with a look at the economic impacts for NSB and also possible socio-economic gains.

Appendices

SWOT Model

SWOT analysis was introduced in the 1960-1970s and emerged because there was a need to find out why corporate planning failed. The SWOT analysis is an extremely useful tool for understanding all sorts of situations and eases the decision-making. SWOT is an acronym for Strengths, Weaknesses, Opportunities and Threats. It gives a good framework for reviewing an idea and is a subjective assessment of data, which is organized by the SWOT format. It can also be used for workshop sessions or brainstorming and is a recognized method for gathering, structuring, presenting and reviewing extensive planning data within a larger business or project planning process. [60]

It is often presented as a grid, comprising four sections, one for each of the SWOT headings used and interpreted as a 2x2 matrix, as shown in figure 1. In this system the strengths and weaknesses are internal factors, based on the situation inside the company, and opportunities and threats are external factors, based on the situation outside the company. The internal factors are typically in the present, while the opportunities and threats tend to be in the future.

SWOT analysis could show that a proposition is too weak, especially if it is compared to the SWOT analysis of other propositions, thereby removing the need for further planning or evaluation of the proposition. It could also show that a proposition is strong and then give incentives to proceed forward with deeper analysis of the proposition. This reduces the work needed and makes it possible to focus on the important aspects.

Figure 1: SWOT Analysis Explained. [61]

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